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RELATION OF SOIL MOISTURE TO DESERT VEGETATION[1]

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(WITH FOUR FIGURES)

INTRODUCTION.—Of a number of lines of study now in progress, looking toward some quantitative knowledge of the relation obtaining between vegetation and environmental conditions, the determination of the march of soil moisture at Tucson has now progressed sufficiently far to warrant publication. The present paper deals with a continuation of the data upon soil moisture published by the writer under the title: "The soils of the Desert Laboratory domain" in SPALDING'S recent monograph on desert ecology (1). The data there presented comprise observations on soil moisture content extending over the period from October 1907 to April 1908. The period of observation has now been extended to March 1909, thus including both the spring dry season and that of the summer rains. To make the present presentation complete, the observations already published are here included.

RELATION OF SOIL MOISTURE TO OTHER FACTORS.—Just as the evaporating power of the air and the nature of the transpiring organs practically determine the water requirement of plants, so do the soil moisture content and the nature of the root system determine the water supply. Aside from those cases (of toxic soils and soils of high osmotic pressure) where the nature and amount of the solutes in the soil solution exert an influence upon the character of the root system or upon the rate of water absorption by these organs, and aside from those cases where the chemical content of the atmosphere or the character or intensity of illumination exert an influence upon the structure of the transpiring organs or upon the general tone of the plant, the simple relation between soil moisture and the evaporating power of the air appears to be of prime importance in determining the character of the natural vegetation. Over an area such as that here considered, where the air and light conditions are approximately uniform, and where the chemical content of the soil appears not to vary sufficiently to produce variations in plant growth, the possible rate of water supply to plant roots may be supposed to become the limiting condition. This rate of supply depends primarily upon the absolute amount of soil moisture and upon the water-conducting power of the soil.

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[1] Publication from the Botanical Laboratory of the Johns Hopkins University, No. 16.

Soil moisture, of course, depends upon the rate of influx and the rate of removal of water from the soil. The former is determined by the ability of the soil to raise water from the subterranean water table, where such exists, by the amount and time of precipitation or other water entering the soil from above or laterally, and by the water-retaining power of the soil. Water removal from the soil is a resultant of evaporation at the soil surface, downward movement into lower layers, and plant absorption.

Throughout the area here studied precipitation is approximately uniform. Surface drainage, nearly uniform within the extent of each soil type, is quite different (because of variations in slope and porosity) for the four types. The water-retaining powers of the four soils are also different. Underground drainage is very different for the different soils, as is also the depth of permanent subterranean water, which is practically quite absent from two of the soils.

THE SOIL TYPES.—The geology and topography of the Tumamoc area are thoroughly described by TOLMAN in the monograph of SPALDING above cited. Tumamoc Hill, on which the Desert Laboratory stands, rises abruptly from the broad valley of the Santa Cruz River. The valley floor slopes very gently from the base of the hill to the river floodplain and to the various "washes," tributaries of the main river channel. The four soils here considered may be briefly described as follows. A more complete description is included in the author's article above cited.

1. The soil of Tumamoc Hill is a heavy clay, underlaid by practically impervious rock at a depth of but 10–50 cm., and much broken into small pockets and irregular masses by outcropping rock or large rock fragments. Fully 50 per cent of the entire gross volume of the soil is made up of large and small rock masses. A subterranean water table does not exist here, so far as is known, and, from the impermeability of the underlying rock both to water and to plant roots, it is safe to conclude that the water supply for this soil is derived exclusively from precipitation. The unsifted soil possesses a water-holding power of 48 per cent of its dry weight. The usually pronounced slope of the soil surface here is partially offset by the numerous small catchbasins formed by rock fragments, so that rain water stands in small pools over the hill and does not drain away quite so rapidly as though the surface were more even.

2. The soil of the *Larrea* slope, so named from the prevalence of the creosote bush thereon, occupies the gentle slope which surrounds the hill. This soil is underlaid at a depth of 20–30 cm. by the limestone hardpan (caliche) so common in this region. The surface soil is more loamy than that of the hill, with an admixture of about half its volume of fine angular gravel; that near the caliche contains even more gravel and rock fragments, sometimes rounded pebbles. The slope, the smoothness and impermeability of the hardpan, the presence of rock fragments, and the loamy nature of the soil itself, all tend to make this a very well-drained soil. It, like the hill soil, is not influenced by subterranean influx of water. Unsifted soil from near the surface possesses a water-holding power of only about 20 per cent. This low retaining power is not here due to general coarseness of the soil, but to the large proportion of angular gravel, which of course holds practically no water.

3. The soils of the wash, a broad streamway from the Tucson mountains, which cuts through the general valley floor (*Larrea* slope in this vicinity) near the northern base of the hill, vary from gravel through sand to very loamy sand. The coarser soils are practically without vegetation and are of little interest in this

connection. The loamy sand, constituting little floodplains on the margins of the actual streamway, is 30 cm. or more in depth and is underlaid by coarser material. This is the soil here considered. It is practically without gravel admixture and has a water-holding power of about 25 per cent of its dry weight. It is almost certain (but without direct evidence) that an underground water table is present here, at least for many months of the year. The soil surface is nearly level and water is received from the superficial run-off of the hill and *Larrea* slope; however, it is well drained below.

4. The soil mass of the river floodplain, now completely abandoned by the stream, is of unknown depth. The surface layer is level and composed of clay loam with a water-holding power of about 39 per cent of its dry weight. This is about 8–9 meters deep and rests on sands and gravels, permanent water being met with at a depth of 10–15 meters. This soil is characterized by general absence of surface run-off and by but slow percolation to lower layers. The dry soil of the deeper layers, however, removes moisture from near the surface as rapidly as it can move downward by capillary action.

THE PLANT SOCIETIES.—The plant societies of the area about the Desert Laboratory have been thoroughly described by SPALDING in the work already mentioned, and also in a journal article (2). THORNBER'S ecologically classified list of species for this region (pp. 103–112 of the same monograph) is of especially great value to the student of environmental factors. The four types of vegetation which occupy respectively the four soil types here considered may be briefly characterized as follows:

1. The *Parkinsonia* society of Tumamoc Hill possesses more forms, both woody and non-woody, than any other of the four societies here considered. Besides this form of palo verde (*Parkinsonia microphylla*), the group includes the giant cactus (*Cereus giganteus*), the ocotillo (*Fouquieria splendens*), the barrel cactus (*Echinocactus Wislizeni*), several opuntias of both cylindrical and flat-stemmed types, *Acacia constricta*, *Larrea tridentata*, *Celtis pallida*, small specimens of mesquite, etc. *Bigelovia Hartwegii* occurs here but does not attain as great numbers or as large size as on the

river plain, where it is more characteristic. Numerous low forms are active throughout the year, notably *Encelia farinosa*, *Sphaeralcea pedata*, etc., and a great array of summer and winter forms are to be found at the proper season.

2. The *Larrea* society of the gravelly slope exhibits, in many localities, almost no woody species other than the creosote bush (*Larrea tridentata*). The bushes are uniformly and openly distributed over a surface which is otherwise nearly bare of vegetation, excepting during early spring and late summer, when numerous low forms appear. Of the desert shrubs within its climatic range, *Larrea* seems best fitted to withstand prolonged drought both of air and soil. *Ephedra* occurs upon the slope as well as in the wash, but makes its best growth in the latter place.

3. The *Cercidium torreanum* society of the wash is characterized by this form of palo verde and by mesquite (*Prosopis*), *Condalia lycioides*, and *Acacia Greggii*. The three latter forms are also characteristic of the *Prosopis* society of the plain. *Ephedra trifurca* and the creosote bush (*Larrea tridentata*) attain here their most luxuriant growth, though the latter, at least, is most characteristic of the *Larrea* society. Aside from these and some other woody plants, the vegetation of the wash consists mainly of small forms, which are active only during the periods of moist soil, either in winter or summer or at both seasons.

4. The *Prosopis* society of the river plain is dominated by mesquite, two forms of *Acacia* (*A. constricta* and *A. Greggii*), and *Condalia lycioides*. Annuals of many forms are numerous during the moist periods. The most striking of the low perennials is *Bigelovia Hartwegii*, which scarcely occurs outside this group, except for scattered plants in the *Parkinsonia* society.

METHODS OF DETERMINING AND OF REPRESENTING SOIL CONDITIONS.—The method used in determining the water-holding powers given above was to place the soil in a sheet-metal cylinder about 12 cm. high and 10 cm. in diameter, with perforated bottom (the latter covered externally with thin cloth), then to saturate the soil by standing in a vessel of water, at the same time pouring water on the soil surface, and finally to allow the soil mass to drain till no more liquid water came away below. From the weight of the dry and saturated soil the water-retaining power is calculated in the usual way (**3**).

The actual soil moisture content was determined by the weighing and drying method, the temperature of drying being 105–110° C. The samples were taken, by digging, at depths of 15 and 30 cm. for all soils but that of the *Larrea* slope. For the latter soil, on account of its shallowness, the depths were 10 and 20 cm. Samples for each soil type were taken from the same area of a few square meters, the small excavations being immediately refilled. No later sample was taken from within 50 cm. of the soil thus disturbed. On December 13 irrigation water made it necessary slightly to change the position of the station for the soil of the floodplain, otherwise the stations remained the same throughout the whole period. Samples were taken at intervals of about 10 days. Three samplings were omitted for all soils during the month of June 1908. A few other omissions of single samples occur.

The specific gravities of these fours soils are approximately the same, there being almost no content of organic matter. Therefore the moisture contents are calculated on the basis of the dry weight of the soil and are here approximately comparable.

The careful work of Mr. J. C. BLUMER, Mr. E. E. SHERFF, and Professor J. E. KIRKWOOD, who performed the operations of collecting, weighing, and drying the soil samples, as well as that of keeping the rain record, is here gratefully acknowledged.

The accompanying graphs (figs. 1–4) have been constructed for each soil separately; the lesser depth is represented by a thin line and the greater by a heavy line. The precipitation record was kept for the hill station alone, but there is no reason to doubt that the rain record for the other stations would have been essentially the same had it been actually taken. For easy comparison, the rainfall is represented below the graphs of soil moisture simply by vertical, shaded blocks, the length of each block denoting the relative amount of precipitation which took place during the corresponding ten-day period. The figures directly above these blocks denote the precipitation in centimeters, that is, the relative length of the blocks. The data from which the moisture graphs are constructed are placed upon the figures directly above the base

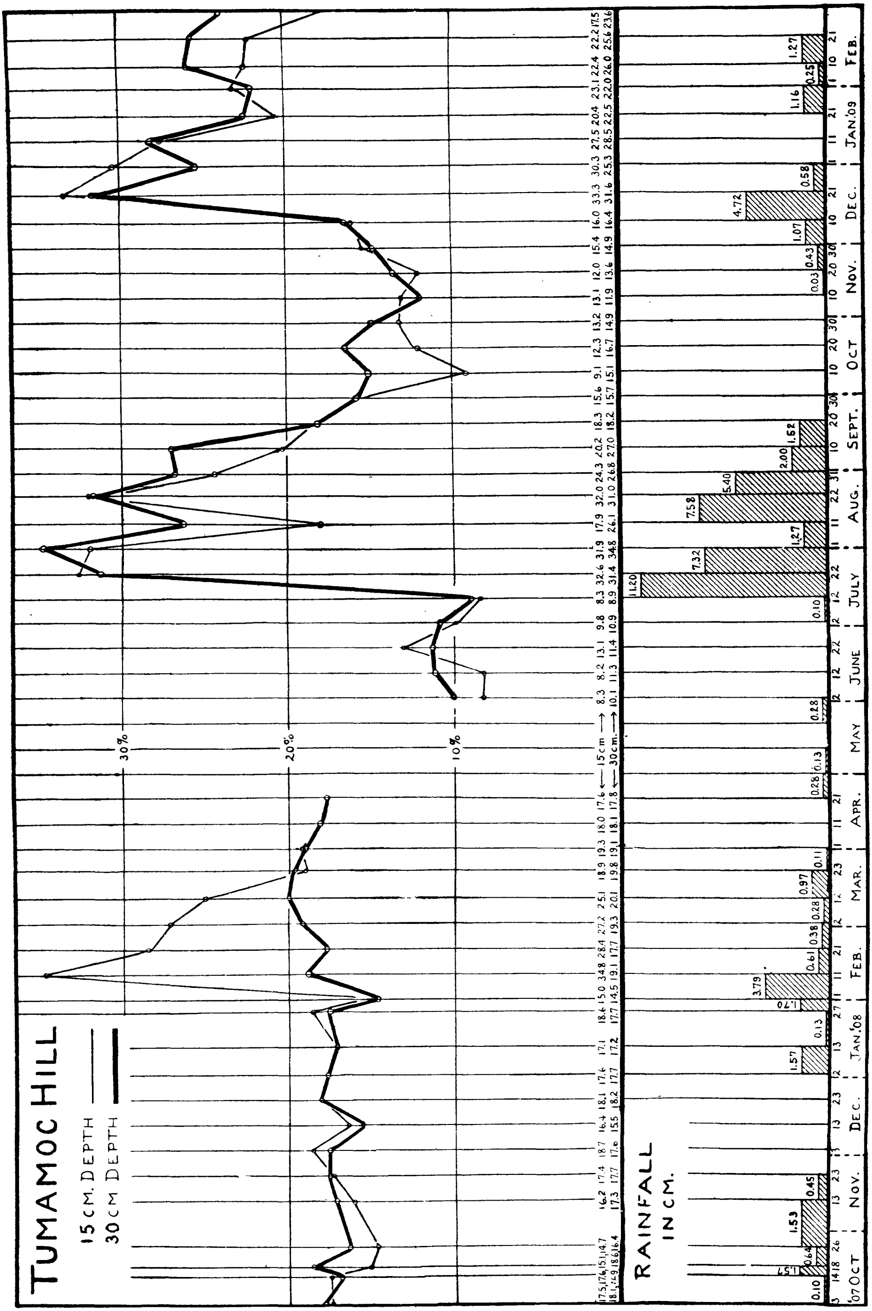
TUMAMOC HILL
15 CM. DEPTH
30 CM DEPTH
30%
20%
10%
17.5 17.6 15.1 14.7 16.2 17.4 18.7 16.4 18.1 17.6 17.1 18.6 15.0 34.8 28.4 27.2 25.1 18.9 19.3 18.0 17.6 ← 15cm → 8.3 8.2 13.1 9.8 8.3 32.6 31.9 17.9 32.0 24.3 20.2 18.3 15.6 9.1 12.3 13.2 13.1 12.0 15.4 16.0 33.3 30.3 27.5 20.4 23.1 22.4 22.2 17.5
18.1 14.9 18.6 16.4 17.3 17.7 17.6 15.5 18.2 17.7 17.2 17.7 14.5 19.1 17.7 19.3 20.1 19.8 19.1 18.1 17.8 ← 30cm. → 10.1 11.3 11.4 10.9 8.9 31.4 34.8 26.1 31.0 26.8 27.0 18.2 15.7 15.1 16.7 14.9 11.9 13.6 14.9 16.4 31.6 25.3 28.5 22.5 22.0 26.0 25.6 23.6
RAINFALL
IN CM.
0.10 1.57 0.64 1.53 0.45 1.57 0.13 1.70 3.79 0.61 0.38 0.28 0.97 0.11 0.28 0.13 0.28 0.10 11.20 7.32 1.27 7.58 5.40 2.00 1.52 0.03 0.43 1.07 4.72 0.58 1.16 0.25 1.27
'07 OCT. NOV. DEC. JAN.'08 FEB. MAR. APR. MAY JUNE JULY AUG. SEPT. OCT NOV. DEC. JAN.'09 FEB.

FIG. 1

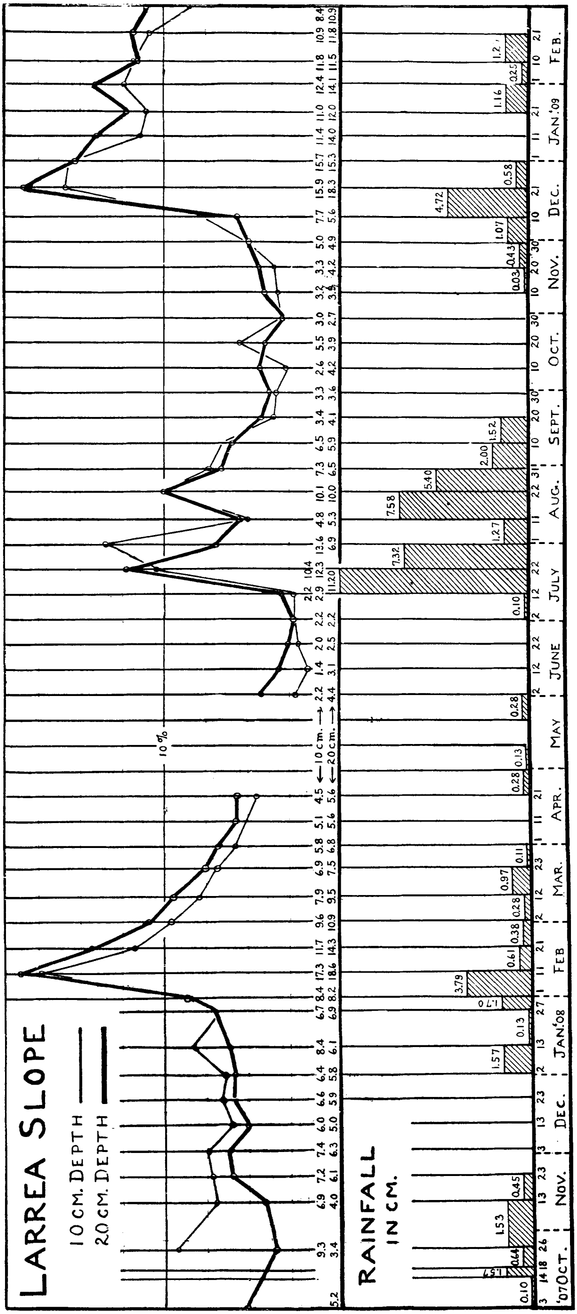
LARREA SLOPE
10 CM. DEPTH
20 CM. DEPTH
RAINFALL IN CM.
10%
←10 cm.→
←20 cm.→
'07 OCT.
NOV.
DEC.
JAN.'08
FEB
MAR.
APR.
MAY
JUNE
JULY
AUG.
SEPT.
OCT.
NOV.
DEC.
JAN.'09
FEB.

FIG. 2

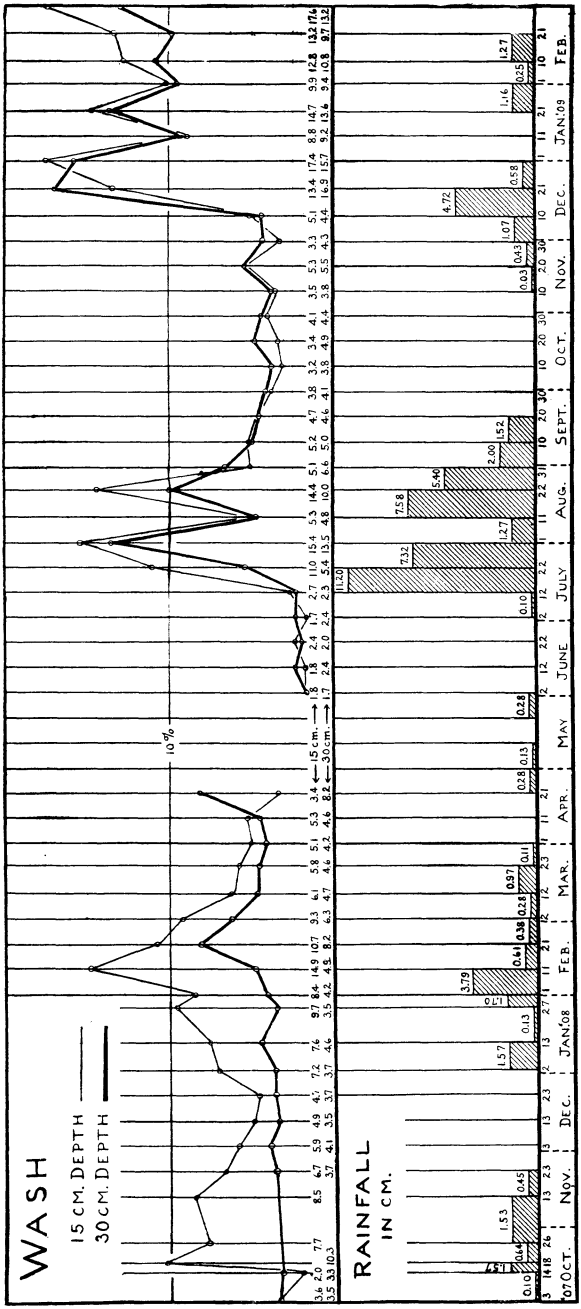
WASH
15 CM. DEPTH
30 CM. DEPTH
10%
15 cm.
30 cm.
RAINFALL
IN CM.
'07 OCT.
NOV.
DEC.
JAN.'08
FEB.
MAR.
APR.
MAY
JUNE
JULY
AUG.
SEPT.
OCT.
NOV.
DEC.
JAN.'09
FEB.

FIG. 3

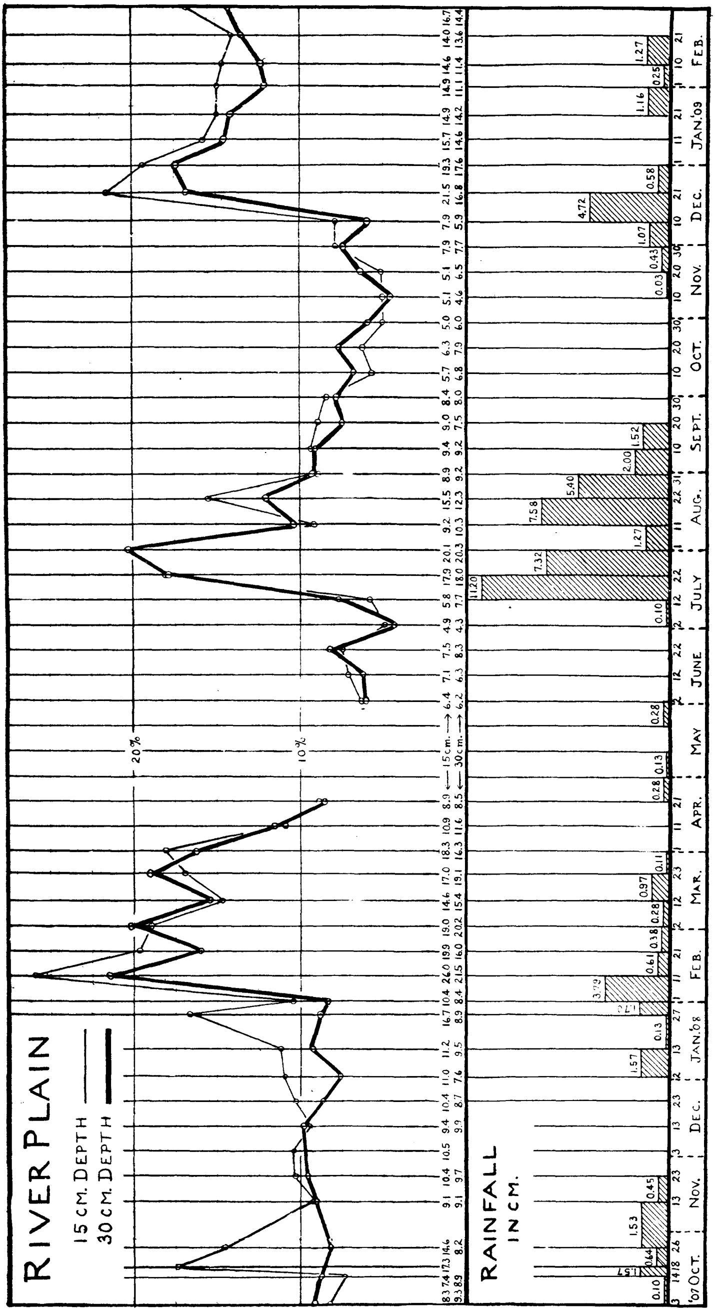
RIVER PLAIN
15 CM. DEPTH
30 CM. DEPTH
20%
10%
15 cm. →
30 cm. →
8.3 7.4 17.3 14.6 9.1 10.4 10.5 9.4 10.4 11.0 11.2 16.7 10.4 26.0 19.9 19.0 14.6 17.0 18.3 10.9 8.9 6.4 7.1 7.5 4.9 5.8 17.9 20.1 9.2 15.5 8.9 9.4 9.0 8.4 5.7 6.3 5.0 5.1 5.1 7.9 7.9 21.5 19.3 15.7 14.9 14.9 14.6 14.0 16.7
9.3 8.9 8.2 9.1 9.7 9.9 8.7 7.6 9.5 8.9 8.4 21.5 16.0 20.2 15.4 19.1 16.3 11.6 8.5 6.2 6.3 8.3 4.3 7.7 18.0 20.3 10.3 12.3 9.2 9.2 7.5 8.0 6.8 7.9 6.0 4.6 6.5 7.7 5.9 16.8 17.6 14.6 14.2 11.1 11.4 13.6 14.4
RAINFALL
IN CM.
0.10 1.57 0.64 1.53 0.45 1.57 0.13 0.61 0.38 0.28 0.97 0.11 0.28 0.13 0.28 0.10 11.20 7.32 1.27 7.58 5.40 2.00 1.52 0.03 0.43 1.07 4.72 0.58 1.16 0.25 1.27
'07 OCT. 3 14 18 26
NOV. 1 13 23
DEC. 3 13 23
JAN.'08 2 13 27
FEB. 1 11 21
MAR. 2 12 23
APR. 1 11 21
MAY
JUNE 2 12 22
JULY 2 12 22
AUG. 1 11 22 31
SEPT. 10 20 30
OCT. 10 20 30
NOV. 10 20 30
DEC. 10 21
JAN.'09 1 11 21
FEB. 1 10 21

FIG. 4

line of these graphs. They express percentage of dry weight. At the base of each figure, the dates of sampling are indicated. The major portion of the calculations and of the drawing of the graphs are the work of GRACE J. LIVINGSTON.

DISCUSSION OF GRAPHS.—It is to be remembered that several simultaneous samples at the same station would be expected to vary to some extent, especially in the stony soil of the hill and of the deeper layer of the slope. Therefore it is not surprising to note minor fluctuations in the graphs, which do not appear traceable to conditions of precipitation.

The graphs bring out clearly the lagging of soil moisture behind precipitation; it requires considerable time for rain water to reach the upper level of sampling and a still longer time for it to reach the lower level. A slight precipitation may not alter the condition of the soil at either level, the water being lost by evaporation before it can penetrate even to a depth of 10 or 15 cm. It also occurs that a rain which is only sufficient to moisten the surface layers, thus placing them in capillary connection with the deeper ones which are already moist, may actually accelerate the drying out of the deeper layers. Thus a slight rain is sometimes directly deleterious to the vegetation; it removes the dry mulch from the surface and fails to add markedly, if at all, to the deeper moisture content, so that before the dry mulch can regenerate, the deeper soil has lost considerable water by upward movement and evaporation.

From data given in *Publication 50* of the Carnegie Institution (pp. 66, 67) it appears that a number of plants of the hill, when grown in pots (in hill soil), wilted with a soil moisture content of 6–12 per cent by wet volume. On the basis of dry weight these numbers become about 7 per cent and 14 per cent. *Boerhavia* (one of the summer annuals of the hill) wilted in the open soil with a moisture content of 6–7 per cent by wet volume, or about 7–8 per cent on the basis of dry weight. These observations were taken in July and August, the period of the summer rains, when the evaporating power of the air was far below its magnitude of May and June or of October and November. With greater evaporation rate, the plants should of course wilt with a correspondingly higher soil moisture content. It is probably safe to assume, therefore, that during the driest months of the year the majority of the plants of the hill require an amount of soil moisture of 8–10 per cent. With a drier soil than this it is probable that most forms without pronounced storage organs would succumb in a few weeks.

No determination of wilting points is as yet available for the other three soils, but from the well-known fact that the "non-available water" in soils decreases, in general, with their water-holding power, it is probably safe to assume that vegetation can withstand a considerably drier soil in the case of the slope and wash, and a somewhat drier one in the case of the river plain.

From the graphs it is evident that the period of most intense drought occurs just before the beginning of the summer rains. In general, the month of June may be taken as the month of driest soils, and it is also the month of greatest evaporation. Therefore, for plants without well-developed water storage tissues, this month must approximate the critical period of the year so far as the water relation is concerned. It will therefore be instructive to derive the average soil moisture content for this month in the case of each of the four soil types. So far as I am aware, the root systems of all plants of this area, which are without storage tissues and which are not annuals, penetrate into the soil at least to the greater of the two depths here considered. We may therefore consider the greater depth alone. The following table presents these averages for the four determinations taken from June 2 to July 2, 1908. The water-holding capacities are also given, and the water content as percentage of the latter.

SOIL MOISTURE AT THE CRITICAL PERIOD

SOIL TYPE	WATER-HOLDING POWER, IN PERCENTAGE OF DRY WEIGHT	AVERAGE MOISTURE CONTENT, JUNE 1908		
		Depth in cm.	Percentage of dry weight	Percentage of water-holding power
Hill	48	30	10.9	22.7
Slope	20	20	3.1	15.5
Wash	25	30	2.1	8.4
Plain	39	30	6.3	16.1

That the vegetation of the hill is the most varied and the most perennially active of all the plant societies of our area, agrees well with the high soil moisture content (almost 11 per cent) and the high percentage of the moisture-retaining power (almost 23 per cent) which this soil exhibits during the driest month of the year. It is to be remembered in this connection that the soil of the hill is often considerably over 30 cm. in depth, and that, in the dry season, the highest moisture content is to be expected just above the underlying rock surface. In the summer of 1904, immediately preceding the advent of the July rains, a soil sample from a depth of 35 cm. on the hill exhibited a moisture content of 17.9 per cent of its dry weight. From the graph of the hill soil and from this last consideration may be derived convincing additional evidence in favor of the conclusion expressed by SPALDING and by the author (*Publication 50*, Carnegie Inst., p. 12) "that sufficient moisture is probably at all times present in the deeper layers of these soils [of the hill] for the needs of transpiration and even growth." The excellent soil conditions exhibited by Tumamoc Hill are emphasized by the fact that at no time during the period of record did the observed moisture content at a depth of 30 cm. fall below 8.9 per cent, and that it was far above 11 per cent at all times excepting in the months of June and November 1908.

The soil of the *Larrea* slope, at a depth of 20 cm., just above the caliche hardpan, exhibited only 3.1 per cent of moisture as the June average. Had the soil been sifted, the moisture content would undoubtedly have been markedly greater, as is indicated by the high percentage of its retaining power (15.5 per cent) which the moisture content represents. But the amount of water available for plants must be considered as a vanishing quantity at this time.

In this vicinity, practically the only perennially active plant on the slope, excepting a few scattered cacti and here and there a plant of *Fouquieria* (itself hardly perennially active), is the creosote bush, from which the slope is named. This plant, as has been mentioned, is probably the most resistant to drought conditions of all non-storage forms in the region. An inspection of the graph for this soil brings out the fact that the moisture content rose above 10 per cent only in February and March, in July and August 1908, and in the winter of 1909. In distinct opposition to the soil of the hill, this soil is undoubtedly deficient in moisture for by far the greater part of the year. It usually supports spring and summer annuals for a few weeks during each of its moist periods.

The soil of the wash shows an even more inadequate moisture supply for the month of June than does that of the slope. This soil contains practically no gravel in its superficial layers and its moisture content at this time (2.1 per cent by dry weight) was only 8.4 per cent of its water-holding power. From the general aspect of the vegetation it would be concluded that this soil was better supplied with moisture than that of the slope, but the graph fails to explain this view. The discrepancy is apparently due mainly to the great depth of the soil, which acts as a much more extensive reservoir for water than the shallow soils of hill and slope. The presence of underground water is doubtless effective in case of those trees and shrubs the roots of which penetrate deeply. The continuously active forms which occur here must be considered as much more deeply rooted than is possible on the hill and on the slope.

The soil of the river plain exhibits a much more favorable moisture condition, not only in June, but throughout the year, than any other of our four soil types excepting that of the hill. Its average water content for the drought period was 6.3 per cent by dry weight. In terms of its moisture-holding power, this becomes 16.1 per cent. This is a deep soil, with unknown, but surely considerable, amounts of moisture below the limits of sampling. It also has constant subterranean water at depths which can probably be reached by tree roots. This latter fact seems to explain the occurrence here of mesquite, acacia, and other deep-rooting shrubs. In the dry seasons (early summer and late autumn) this soil shows very few active plants besides those just mentioned, but in the rainy seasons it supports a dense growth of annuals, being apparently as well suited to such forms as is the soil of the hill itself. That many annuals of the hill fail generally to appear on the plain, and conversely, is perhaps to be explained by the considerably higher moisture content occurring during the rainy seasons on the former soil. It may also be related to conditions which hinder surface evaporation on the hill, such as the presence of numerous rock fragments on or in the soil.

An interesting question is suggested by the fact that the creosote bush dominates the slope and occurs on the hill, but is almost entirely absent from the plain, excepting along the margin where it abuts against the slope. No evidence as to why this shrub should not thrive on the plain is as yet at hand. The most vigorous specimens of the area occur along the lower margins of the slope, which agrees with a similar behavior always observed in irrigated specimens, in seeming to indicate that a more adequate water supply produces an abnormally great growth. SPALDING mentions the physiographical relation (which of course cannot *directly* affect the vegetation) that *Larrea* usually dominates gentle slopes which are being eroded at the present time. It would seem that there must be some condition in the soil of the plain which is antagonistic to the growth of this shrub. A study of the oxygen conditions of these soils may possibly throw some light on the subject. The moisture condition alone is inadequate to explain the facts.

The results obtained from a study of the graphs would place the hill soil first, as the best suited for general plant activities; the soil of the plain would occupy second place, and the two other soils would lie rather close together and far below either of these. This general arrangement agrees well with the vegetational characters of the four soil types if we consider that the deep-rooting forms of wash and plain obtain moisture from levels deeper than those here considered. It is also in fair agreement with the simple series of the water-retaining powers of the four soils. From this retaining power alone the soils would have been interpreted in the same general way. This emphasizes the water-holding power as an easily obtained and very important factor in studies of distribution.

The last-named factor has been used by the writer (4) with some success in a search for the determining conditions of forest distribution in Michigan. It appears that for different upland habitats of the same region, where the level of underground water is far from the surface, and the precipitation and evaporating power of the air are approximately uniform, the relative soil moisture conditions may be fairly well approximated by the criterion of water-holding power. The ease of obtaining comparative data for this factor entitles it to a thorough test as a soil criterion for habitat studies.

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